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PLANT DESIGN

APPLIED TO CONTINUOUS DEHYDRATION WITH DIETHYLENE GLYCOL

A THESIS

PRESENTED TO THE FACULTY OF THE GRADUATE SCHOOL OF CORNELL
UNIVERSITY FOR THE DEGREE OF

MASTER OF SCIENCE IN ENGINEERING

BY

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BIOGRAPHY OF AUTHOR

The author was born in Brooklyn, N.Y. February 11, 1918. He attended local elementary schools, and graduated from New Utrecht High School in 1935. After graduation from high school he obtained work as a knitter-machinist, attending City College of New York at night. In 1937, he enrolled in City College School of Engineering in the full-time day course, receiving the degree of Bachelor of Chemical Engineering in June 1941.

From June 1941 until February 1943, he worked for the Blaw-Knox Company of Pittsburgh, Pa. as a design engineer on natural-gas dehydration equipment.

After joining the United States Navy in 1943, he was sent to Cornell Diesel School for training and subsequently served two years as an engineering officer on a small Naval vessel.

In July 1945 he was accepted for a postgraduate course in Ordnance Engineering (Explosives) and sent to Cornell University to study Chemical and Explosives Engineering.

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INTRODUCTION

Until rather recently, transmission lines for natural gas operated under pressures only slightly above atmospheric pressure. Even in these low-pressure lines, deposits of white crystals were observed occasionally. Since these deposits appeared only at temperatures considerably below the freezing point of water, it was rather generally thought (10) that they consisted merely of ice crystals. The amount of "snow" deposited in the lines was so small that it did not cause serious operating trouble; its importance did not appear to justify critical study. In rather recent years, high-pressure transmission lines for natural gas have come into very common and very extensive use. In these high pressure lines, the deposition of the white solid occurs in such quantity as to cause clogging of the lines and serious fouling of valves and orifices. Furthermore, at high pressures, in the range of 500 pounds per square inch, the crystals may deposit at temperatures as high as 50°F (2).

Early in the history of the high-pressure transmission of natural gas, it was found that these "snow" crystals are really crystalline hydrates of some of the lower paraffin hydrocarbons, as for example, $CH_4 \cdot 6H_2O$ and $C_2H_6 \cdot 6H_2O$.

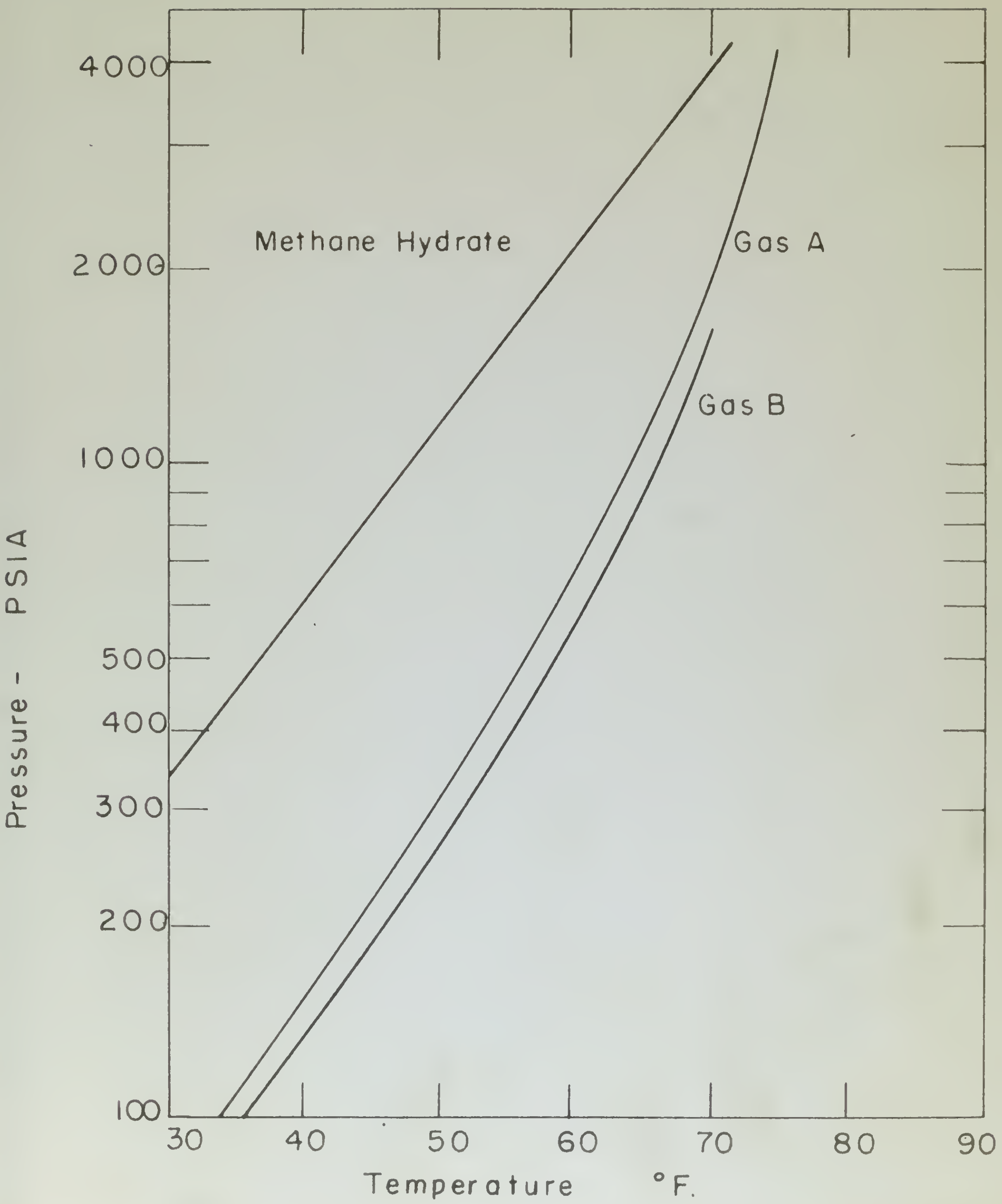
In the past decade, a considerable amount of research has been done on the formation and properties of these hydrates and on methods for preventing their formation. (3)(4)(8)(9)(10)(11)

THE CAUSES OF HYDRATE FORMATION

The formation of natural gas hydrates depends primarily on temperature, pressure, and composition of the gas. As shown by Graph 1, both high pressure and low temperature are favorable to the formation of hydrates. Favorable temperature and pressure are not the only criteria for hydrate formation. The gas must be almost saturated with respect to water vapor, since these hydrates will not form until the dew point is approached. If the partial pressure of the water vapor in the gas is less than the vapor pressure of the gas hydrate, the hydrate looses water and decomposes. Also indicated in Graph 1 is the fact that hydrates form at slightly different pressures and temperatures depending upon the composition of the natural gas.

A definate temperature, pressure, and composition are necessary before the gas hydrate can form. However, even if these conditions are established, it is by no means certain that the hydrates of the lower paraffin hydrocarbons will crystallize out. There are then certain secondary factors which influence the formation of gas hydrates. It has been found (2) that high velocities of the gas stream, pressure pulsations, or the introduction of a small hydrate crystal all promote the formation of the

GRAPH 1



FAVORABLE CONDITIONS FOR THE FORMATION OF NATURAL-GAS HYDRATES

hydrates. Both pressure pulsations and high velocities are encountered in transmission lines.

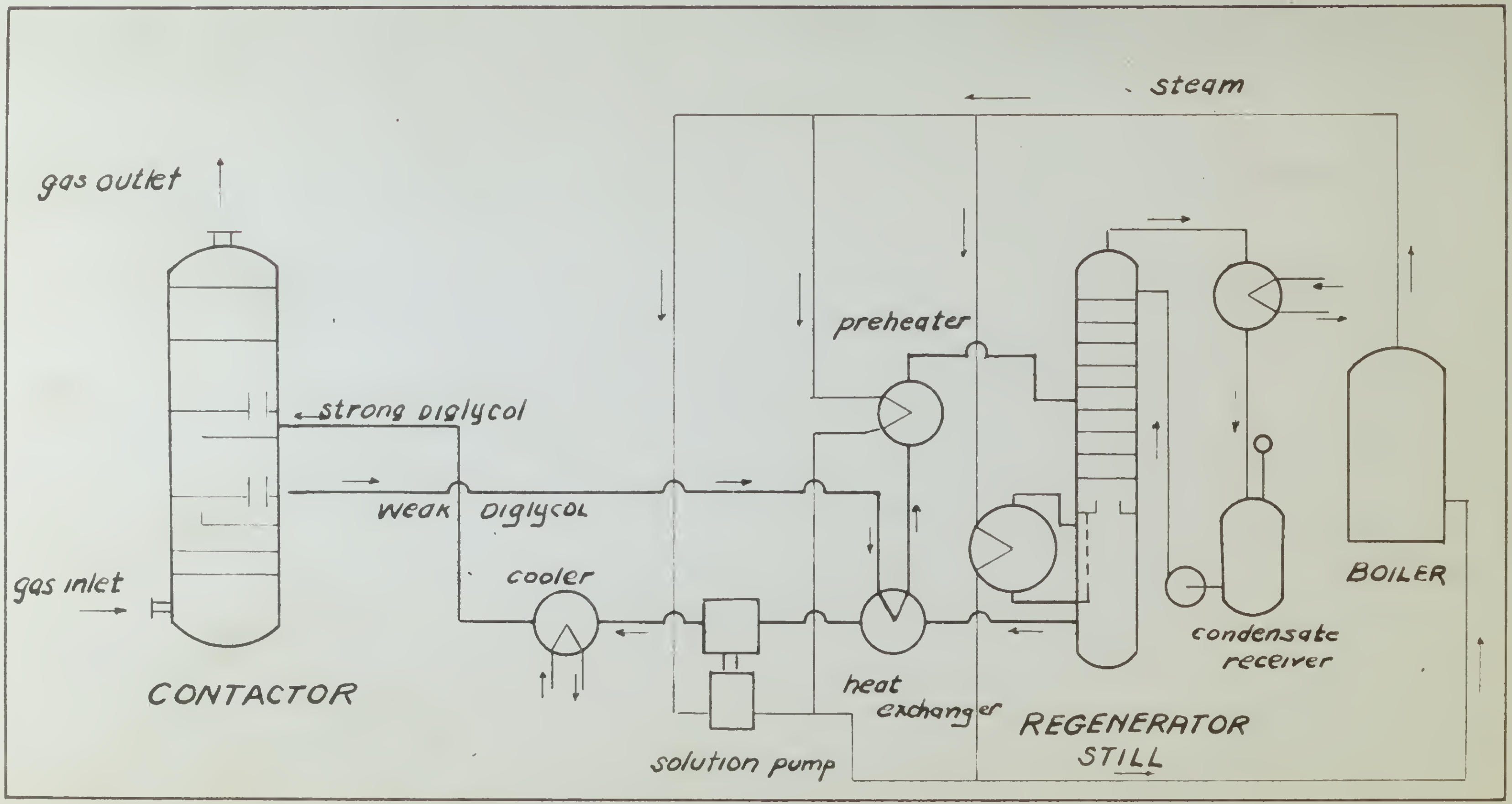
The curves of pressures and temperatures necessary for hydrate formation in an actual gas show a change in slope at about 66°F. This is significant in that the actual equilibrium temperature at 4,000 pound per square inch is lower by 5°F. to 10°F. than the values that would be obtained by extrapolating the low-pressure data as a straight line. The change in slope may indicate some change in the hydrate formed, as, for example, lowering the number of water molecules per mole of gas. The number of water molecules per mole of natural gas constituent is not known precisely (2). Early work (8) indicated from 6 to 8 moles of water per mole of hydrocarbon in the crystal. At higher pressures it was found (21) that these valves decrease to 5.3, 4.8, and 4.3 moles of water per mole of hydrocarbon.

THE ELIMINATION OF GAS HYDRATES

Since the formation of natural gas hydrates is a function of temperature, pressure, and composition, the elimination of these hydrates will depend upon the effective control of these variables. The gas emerges from the casing head at the well or from the pumping station at a definate pressure, temperature, and composition. The formation of solid hydrates may be prevented by reducing the pressure of the gas to below the critical valve required for solid formation at the lowest temperature existing in the line, by maintaining the temperature of the gas above the point at which solid hydrate formation can occur at the existing pressure, by adding to the gas some substance that prevents the formation of solid hydrate, or by dehydrating the gas to a dew point lower than the prevailing temperature of the atmosphere surrounding the transmission line so as to prevent saturation of the gas with water vapor.

Lowering the gas pressure is not sound practice. It means the gas must be recompressed for transmission. Expanding the gas to a lower pressure also means a drop in gas temperature. The gas is still saturated with respect to water vapor and at the lower temperature the tendensy for hydrate formation has not been decreased. Rainsing the gas temperature makes the

The present paper is mainly concerned with dehydration by diethylene glycol.



FLOW DIAGRAM OF A
DIETHYLENE GLYCOL DEHYDRATION PLANT

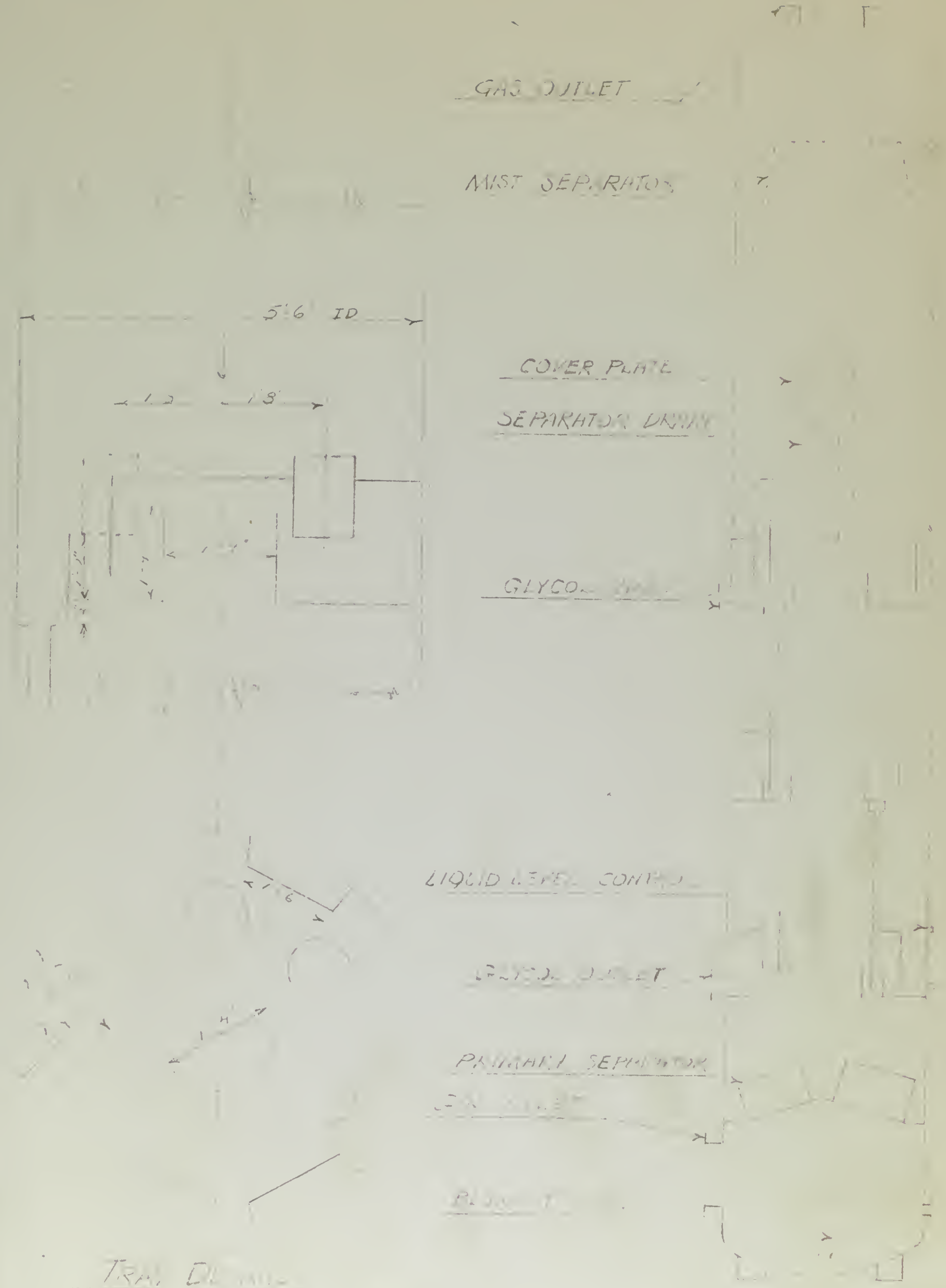
THE DIETHYLENE GLYCOL PLANT

In the continous diethylene glycol plant, high-pressure natural gas saturated with water vapor is passed upward through a contactor in which it is brought countercurrently in contact with diethylene glycol. Since the glycol has a marked affinity for water, it absorbs the water from the natural gas. The gas, freed from most of its initial water content by contact with the glycol, passes from the top of the scrubber to the compressor and the transmission line. The wet diethylene glycol passes from the bottom of the column to a regenerator in which the water is removed. The strong diethylene blycol is pumped back to the top of the contactor.

The plant consists of the following essential units:

1. A contactor
2. A regenerating still with reboiler, condenser, reflux pump, and condensate receiver.
3. A heat exchanger and a preheater (optional)
4. A duplex pump.
5. A boiler to generate steam.
6. Various flow and temperature controls.

The contactor (see diagram) is a column consisting of a gasoline separator on the bottom to extract any natural gasoline entrained with the gas;



GAS CONDITIONING TOWER

two or three sets of double contact plates in the middle portion; and a tracyfier separator to remove any entrained diethylene glycol mist from the gas.

The contacting unit consists of three sets of doubl plates. The upper plate holds a series of uptake pipes which dip into a liquid resevoir of diethylene glycol on the lower plate.

At the start of operation the gas enters under high pressure and forces the liquid up the uptake pipes while the liquid level on the bottom plate drops. When the liquid level on the bottom plate drops to below the rim of the pipes, the gas rushes up the pipe in a swirling motion entraining some of the liquid as mist. The mist tends to separate out when the gas changes direction to pass to the next plate.

This type of column gives good contact with very little pressure drop. The column must be constructed and errected with perfectly horizontal plates.

All the equipment is constructed of standard cold rolled low-carbon steel, according to API-ASME codes. Corrosion is negligible.

The regenerator is a simple bubble-cap plate distilling column, using steam in closed coils in the reboiler, removing water vapor as product (tops) and recovering strong (97 per cent) diethylene glycol from the bottoms.

The reflux receiver is a large vented tank which must be checked periodically to determine if any natural gas or gasoline has been absorbed with the water vapor by the diethylene glycol. This still operates at atmospheric pressure and is designed for a maximum of 50 pounds per square inch absolute.

The steam boiler is a simple horizontal Scotch-Marine type automatically controlled boiler. It uses natural gas as a fuel, tapping the main transmission line thru a pressure reducing valve. The steam is used in the reboiler of the still and in the duplex pump.

The duplex pump is necessary to pump the strong diethylene glycol back into the pressure contactor from the regenerator which operates at atmospheric pressure.

Various controls such as a liquid-level control on the bottom contactor tray, a flow control for the duplex pump, temperature, pressure and automatic cut-off controls on the boiler, temperature control on the reboiler and on the preheater, temperature control for the vapor product of the regenerator to control reflux. All of these controls are necessary to make the plant automatic in operation.

THE DESIGN OF THE DIETHYLENE GLYCOL PLANT

The main purpose of the diethylene glycol plant is the dehydration of the natural gas to a low enough dew point so that the gas is at all times unsaturated with respect to water vapor. As long as the gas is unsaturated, no solid hydrated will form. This implies that the dew point must be lowered to a temperature below the lowest seasonal temperature encountered by the transmission line.

Assuming that the gas emerges from the well or from the pumping station in a condition of saturation with respect to water vapor, there remains only the determination of amount of water vapor that must be removed to drop the dew point to a value low enough to prevent hydrate formation. It would seem that specifying the natural gas temperature and degree of saturation would completely determine the water vapor content. This would be true at low pressures where ideal gas laws and partial pressures hold. However, at high pressures, the vapor pressure of water tends to increase above the equilibrium pressure at normal pressure. This is known as the Poynting effect (6). The water vapor content can be approximated by use of the fugacity at the operating pressure in combination with the compressibility factor. This approximation is not necessary, as Russell (18)(19) has recently determined the equilibrium water vapor content in natural gas at various pressures and temperatures Graph 2*. On this graph the Hammerschmidt hydrate line is indicated. It can be seen that both high pressure and low temperature are necessary for hydrate formation. Graph 2 shows the equilibrium saturation water vapor content at various temperatures and pressures. To estimate the amount of water vapor that must be removed from the gas it is necessary to first determine the water content at the gas line temperature and pressure, and to subtract from this value the water-vapor content at the same pressure but at a temperature corresponding to the lower dew point. This lower temperature is the lowest temperature to which the line may be exposed. The difference between the two water contents represents the amount of water that must be removed if hydrate formation is to be prevented. If the water content in pounds per million cubic feet of standard gas to be removed is now multiplied by the gas plant

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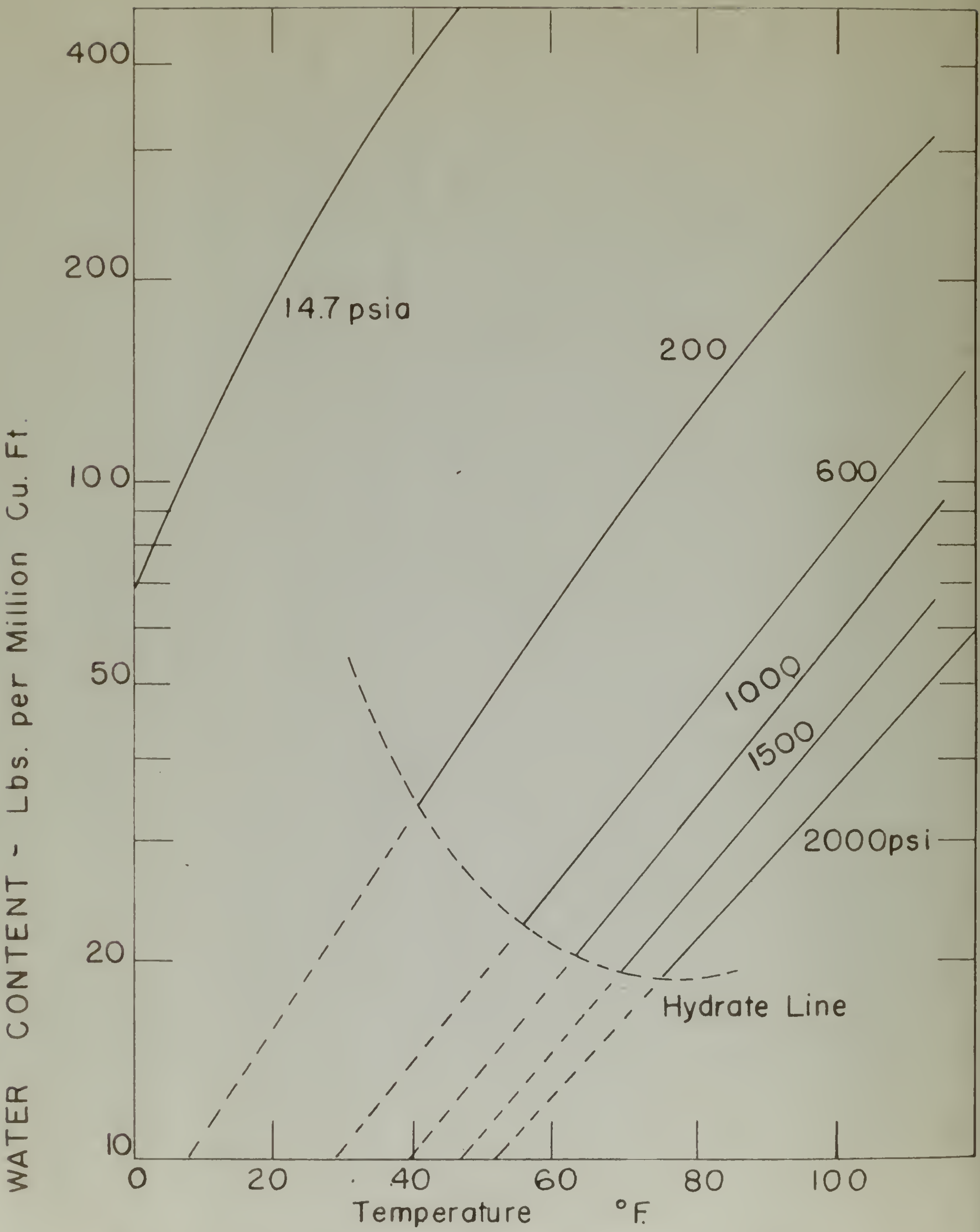
* Many of the graphs in this paper where copied from graphs appearing in the printed literature. Due to the low degree of accuracy, these graphs should not be used for design purposes.

GRAPH 2



EQUILIBRIUM WATER VAPOR CONTENT OF A NATURAL GAS capacity in millions of cubic feet of standard gas per day, the rate of water removal is derived. The accurate computation of rate of water removal is important as it helps determine the rate of glycol circulation.

The determination of the glycol rate is the key to the design of the dehydration plant, because this rate fises the number of contactor plates, the concentration of weak glycol leaving the contactor and also the heat load of the regenerator reboiler. The optimum glycol rate is determined by an economic balance between the number of plates in the contactor and the steam consumption in the reboiler of the regenerator. Before determining the glycol rate, several operating factors must be fixed or assumed.

In a simple material balance around the contactor, the water removed from the natural gas must equal the water absorbed by the liquid diethylene glycol. If the rate of natural gas flow is expressed in pound moles of bone-dry natural gas per hour, the rate of glycol flow as the moles of pure dry glycol per hour and the water concentration in mole ratio, the material balance reduces to:

$$G(Y_B-Y_T) = L(X_B-X_T) \qquad (1)$$

where: G = Moles of dry inert natural gas per hour

L = Moles of pure dry diethylene glycol per hour

Y = Moles water per mole dry gas

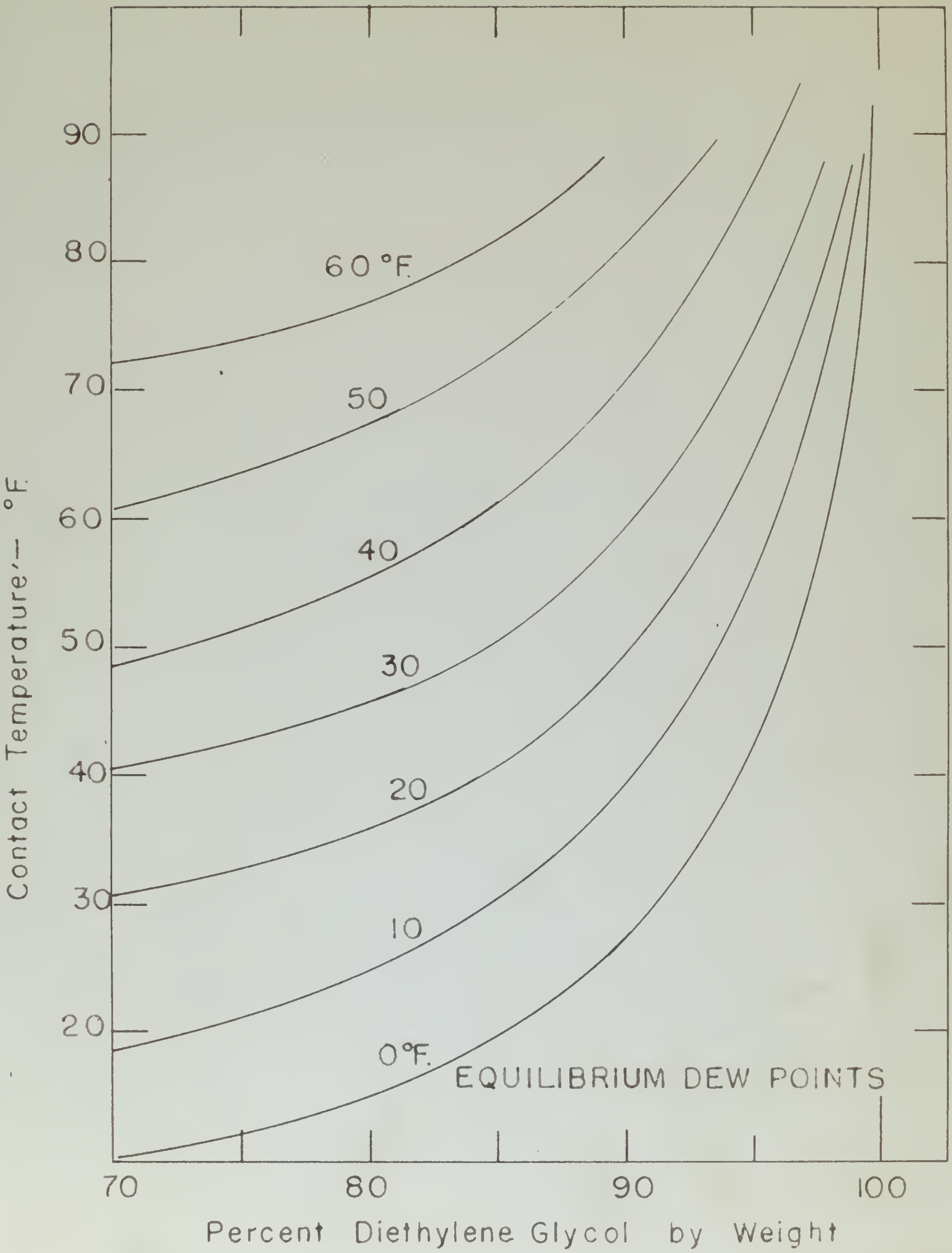
X = Moles of water per mole pure dry glycol

B = Bottom of contactor tower

T = Top of tower

This equation is a simple material balance and, as such, must hold true irrespective of the mechanism of absorption. If it can be assumed that no glycol evaporates in the contactor and that no natural gas is absorbed by the liquid glycol, then G, the dry gas flow, and L, the dry liquid glycol flow, are both constant and the ratio L/G must also be constant. If the ratio of L/G is constant on an X vs Y plot, the operating line must be a straight line with the slope of L/G. This operating line is indicated on Graph 4. On the same graph, the equilibrium between water vapor in the gas and water concentrate in the liquid glycol solution is indicated at the operating temperature. To simplify calculations, the assumption is made that the contacting tower will operate at the temperature of the inlet gas. This is a fair approximation, as the ratio of rate of gas flow to the rate of flow of glycol is so large that, in spite of the large difference in heat capacities, the total tower contents soon approach the temperature of the gas.

GRAPH 4



EQUILIBRIUM DEW POINTS FOR GAS DEHYDRATION

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As stated, the material balance is expressed by the equation:

$$G(Y_B-Y_T) = L(X_B-X_T) \qquad (1)$$

In this equation, G, Y_B, Y_T, and X_T are known or fixed quantities. The rate of flow of glycol (L) and the concentration (X_B) of the outgoing weak solution are not known. Thus we have one equation with two unknowns. In a tower with an infinite number of plates, the minimum ratio of L to G under which the tower could operate would be that corresponding to the tangent of an operating line that just touches the equilibrium line at one point. If the glycol could be passed down the tower with no change in composition, no plates would be needed, but an infinite rate of circulation of glycol would be required. The actual glycol rate and the concentration of weak glycol solution must be fixed by an economic balance. A rough balance indicates that the actual L/G ratio should equal about four times the minimum L/G ratio. The equilibrium curve for 80°F. indicates a minimum L/G of $2.5X10^{-4}$ moles of glycol per mole of dry gas. This corresponds to an actual L/G ratio of $1X10^{-3}$ moles of glycol per mole of dry gas. This ratio automatically fixes the glycol rate. Knowing the glycol rate, the concentration of glycol leaving the tower can be determined from the material balance of Equation 1. Thus, the design of the contactor includes the expression of inlet and outlet water content in mole ratios, the determination of the water-diethylene glycol equilibrium curve at the operating temperature and pressure, and the determination of the minimum L/G ratio. The minimum L/G ratio, together with economic considerations, fixes the actual L/G ratio, the diethylene glycol rate, and the concentration of weak glycol leaving the tower.

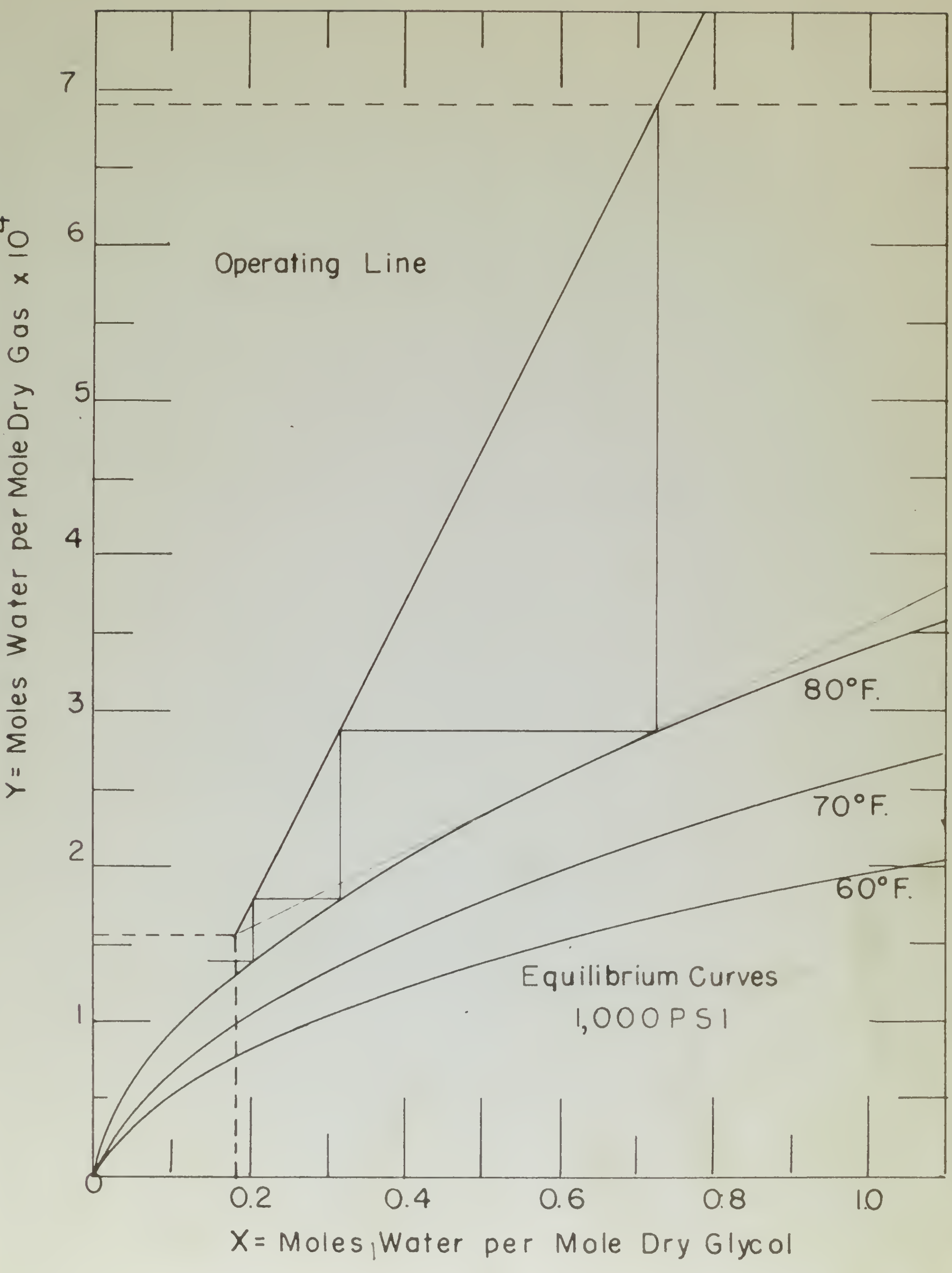
The molar ratio of water to dry gas in the inlet gas is calculated from the line temperature and pressure, on the assumption that the gas is saturated with water vapor. These conditions and Graph 2 are sufficient to fix the moles of water per mole of dry gas. The water content of gas leaving the top of the tower is also found from the same graph using the same pressure. However, the temperature in this case is not the gas temperature but the dew point to which it is necessary to lower the gas from saturation. This dew point is fixed if the geographical position of the transmission line is obtained. To prevent hydrate formation, the gas must remain unsaturated. To remain unsaturated the dew point must always be lower than the gas temperature. Therefore, the dew point to which the gas must be dehydrated must always be lower than the average winter temperature to which the line may be exposed.

The equilibrium curves (Graph 5) are constructed by a combination of Graphs 2 and 4. Graph 4 shows a series of equilibrium dew-point curves for any contact gas temperature corresponding to a definite glycol concentration. The water content corresponding to the equilibrium dew point at the line pressure can be read from Graph 2. Thus a series of equilibrium curves at different temperatures for any one pressure can be drawn. For any other pressure, another family of equilibrium curves is necessary.

To clarify the above procedure a problem will be illustrated.

> Problem: Design a dehydrating plant handling 100 million standard cubic feet per day of natural gas. Gas enters at 80°F. saturated with water vapor at 1,000 pounds per square inch absolute. The gas gravity is o.6. Geographical considerations require the dew point to be lowered to 30°F.

GRAPH 5



Water - Diethylene Glycol - Natural Gas System

1. Rate of water removal

A. Initial water content at 80°F. and 1000 pounds per square inch absolute is

33.0 lb. $H_2O/10^6$ Std. Cu. Ft. (Graph 2)

B. Final water content at 30°F. and 1000 pounds per square inch absolute is

7.3 lb. $H_2O/10^6$ Std. Cu. Ft. (Graph 2)

C. Net water to be removed is

$33.0 - 7.3 = 25.7$ lb. $H_2O/10^6$ Std. Cu. Ft.

D. Rate of water removal per minute is

$$\frac{25.7 \text{ lb. } H_2O/10^6 \text{ Std. Cu. Ft.} \times 100 \times 10^6 \text{ Cu. Ft./Day}}{1440 \text{ Minutes/Day}}$$

$= 1.78$ lb. H_2O/minutes*

II The diethylene glycol rate

1. (L/G)* Minimum is

2.5×10^{-4} Moles Glycol/Moles dry gas (Graph 5)

2. $L/G = 4 \times (L/G)$ Minimum is

1×10^{-3} Moles Glycol/Moles dry gas

3. $$G = \frac{100 \times 10^6 \text{ Std. Cu. Ft./day}}{24 \text{ Hrs./Day} \times 379 \text{ Cu. Ft./Mole}}$$

$= 11{,}000$ Moles/Hr.

4. $L = G \times (L/G) = 11{,}000 \times 10^{-3}$

$= 11$ Moles Glycol /Hr.

$$L = \frac{11 \text{ Moles/Hr.} \times 106 \text{ lb./lb. Mole}}{9.1 \text{ lb./Gallon}}$$

$= 128$ Gal/Hr. $= 2.1$ GPM

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* A list of symbols used appears at the end of this paper.

III Concentration of weak glycol solution

1. $L/G = \frac{Y_B - Y_T}{X_B - X_T}$

a) $Y_B = \frac{33 \text{ lb. } H_2O/18 \text{ lb./lb. Mole}}{10^6/379}$

$= 6.92 \times 10^{-4}$ Moles H_2O/Mole dry gas

b) $Y_T = \frac{7.3/18}{10^6/379} = 1.54 \times 10^{-4}$ Moles H_2O/Moles dry gas

c) X_T = 97% glycol by weight

$= \frac{3/18}{97/106} = 0.182$ Moles H_2O/Moles dry glycol

$L/G = 10^{-3} = \frac{6.92 \times 10^{-4} - 154 \times 10^{-4}}{X_B - 0.182}$

$X_B = 0.72$ Moles water / Mole glycol

$= \frac{106 \times 1}{.72 \times 18 + 106 \times 1} =$ 89% glycol by weight

IV The Contactor Tower

A. Number of plates

From Graph 5, 2.2 theoretical steps are required to reduce the moisture content to the desired point under the specified conditions. This assumes perfect equilibrium is attained on every plate. If we assume a plate efficiency of 75%, this corresponds to 2.2/.75, or 3 actual plates.

B. Tower Diameter

To find the tower diameter, the true volume of flow at 80°F. and 1000 pounds per square inch absolute must be known. This necessitates the determination of the compressibility factor, since the ideal gas law does not hold at 1000 pounds per square inch. For natural gas with a gas gravity of 0.6 the pseudocritical pressure is 670 pounds per square inch absolute and the pseudocritical temperature is 370°R.

$P_r = P/P_{sc} = 1000/670 = 1.49$

$T_r = 540/370 = 1.46$

$Z = 0.87$

The actual volume of gas flow is then:

$$V = \frac{100 \times 10^6 \text{ Cu. Ft./Day}}{1440 \text{ min/day}} \; \frac{540^\circ\text{F.}}{520^\circ\text{F.}} \times \frac{14.7 \text{ lbs. per sq. in.}}{1000 \text{ lbs. per sq. in.}} \times .87$$

$= 925$ Cu. Ft./Min.

The Allowable Gas Velocity is

$v = 127$

for $P = 1000$ lbs. per sq. inch, $t = 80^\circ$F., gas gravity $= 0.6$

then $\rho = 4$ lbs. per. Cu. Ft.

$v = 127 \;\; 1/4$

$v = 63.5$ Ft./Min.

Area = Actual Volume/Allowable Velocity

$$A = \frac{925 \text{ Cu. Ft./Min.}}{63.5 \text{ Ft./Min.}}$$

$= 14.6$ Sq. Ft.

$d = 13.5\sqrt{A} = 13.5\sqrt{14.6}$

$d = 51\frac{1}{2}$ in. diameter

use 52 in.

C. Shell thickness

$$t = \frac{pd}{2SE - p} = \frac{1000 \times 52}{22{,}000 - 1{,}000}$$

$t = 2.47$ inches, or $2\frac{1}{2}$ inch plate

Since this shell is rather thick, it might be economical to investigate the cost of operating two towers in parallel, each having half the area of the original tower.

$A = 7.3$ sq.ft.

$d = 13.5\sqrt{7.3} = 36$ inches

Shell thickness $t = \frac{1000 \times 36}{21000} = 1.72 = 1\frac{3}{4}$ inches.

Two towers of $1\frac{3}{4}$ inch walls would probably be cheaper than one tower of $2\frac{1}{2}$ inches.

D. Uptake Area

1. Allowable velocity = 1200 to 1400 ft./min.
2. Uptake area 925/1200 = 0.77 sq.ft.
3. Divide into six uptakes of 0.13 sq.ft. each
4. Diameter $d = 13.5\sqrt{.13} = 4.86$ inches

   Use 6-5 inch diameter standard pipes.

IV Design of Regenerator Still.

1. Pressure = 1 Atmosphere
2. Allowable vapor velocity = 1 ft./sec.
3. Use reflux ratio of 1 to 1
4. Vapor rising = twice feed water vapor
5. Volume of vapor rising

   = lbs. H_2O/min. x 2 x specific volume of steam at 212°F.

   = 1.78 lbs.H_2O/min. x 2 x 26.8 cu.ft./lb.H_2O

   = 95.4 cu.ft./min.

6. Area = Volume/Velocity = $\frac{95.4}{60}$ = 1.59 sq.ft.

7. d = 13.5$\sqrt{1.59}$ = 17 inches diameter

Use (arbitrarily) 10 bubble cap plates feeding in on the fifth plate.

V Heat Exchanger

1. Use Griscome Russel G fin tubes

2. To cool concentrated diethylene glycol from reboiler temperature of 330°F. to 160°F.

3. To heat weak diethylene glycol feed from 80°F. to 250°F.

4. U = 5 to 10 Btu/sq.ft. x hr. x LMTD

5. Heat load = C_p W t

C_p = 0.525 Btu/lb.°F.

W = GPM x 60 x 9.1 lbs./gallons

t = 170°F.

Q = 0.522 x 2.13 GPM x 60 x 170

= 107,000 Btu/hr.

6. Area = Q/U x LMTD

= 107,000/10 x 80 = 134 sq.ft.

VI Reboiler

1. To heat glycol from 250°F. to 330°F.

2. To vaporize two time the reflux of water vapor

3. Area = Area to heat glycol plus area to heat water vapor plus 20% extra

4. Use steam 135 lb./sq.in. and 350°F.

5. $U = 15$ for heating

$Q = C_p \, W \, T = 0.525 \times 2.31 \times 9.1 \times 80$

$= 52,700$ Btu/hr

$$\text{LMTD} = \frac{\Delta T_1 - \Delta T_2}{\ln \Delta T_1/\Delta T_2} = \frac{100 - 20}{\ln 100/20} = 49.7^\circ\text{F.}$$

Heating Area $= Q/U \times \text{LMTD} = 52,700/15 \times 49.7$

$= 70.6$ sq.ft.

6. U for vaporizing = 30 Btu/hr sq.ft.°F.

$Q = 970 \times 2 \times 1.78 \times 60 = 208,000$ Btu/hr.

$A = Q/U \times \text{LMTD} = 208,000/30 \times 20$

$= 347$ sq.ft.

7. Total Reboiler Area $= A_h + A_v + 20\%$

$A = 70.6 + 347 + 83.5$

$= 501$ sq.ft.

VII Still Condenser

1. $U = 50$ Btu/hr. sq.ft.°F.
2. Use cooling water of 80°F.
3. Condense to 200°F.

$Q = W \times H_{steam}$

$= 970 \times 2 \times 1.78 \times 60 = 208,000$ Btu/hr.

$$\text{LMTD} = \frac{\Delta T_1 - \Delta T_2}{\ln \Delta T_1/\Delta T_2} = \frac{122 - 62}{\text{Ln } 122/62} = 87.7^\circ\text{F.}$$

Area $= Q/U \times \text{LMTD} = 208,000/50 \times 87.7$

$= 47.5$ sq.ft.

5. U=15 for heating

$Q = C_p\ W\ \ T = 0.525 \times 2.31 \times 9.1 \times 80$

$= 52{,}700$ Btu/hr

$$\text{LMTD} = \frac{\Delta T_1 - \Delta T_2}{\ln T_1 / T_2} = \frac{100 - 20}{\ln 100/20} = 49.7^{\circ}\text{F.}$$

Heating Area = Q/UxLMTD = 52,700/15x49.7

= 70.6 sq.ft.

6. U for vaporizing = 30 Btu/hr sq.ft.°F.

Q = 970 x 2 x 1.78 x 60 = 208,000 Btu/hr.

A = Q/ UxLMTD = 208,000/30x20

= 347 sq.ft.

7. Total Reboiler Area = $A_h + A_v + 20\%$

A = 70.6 + 347 + 83.5

= 501 sq.ft.

VII Still Condenser

1. U = 50 Btu/hr. sq.ft.°F.

2. Use cooling water of 80°F.

3. Condense to 200°F.

$Q = W \times H_{steam}$

= 970 x 2 x 1.78x60 = 208,000 Btu/hr.

$$\text{LMTD} = \frac{\Delta T_1 - \Delta T_2}{\ln \Delta T_1 / \Delta T_2} = \frac{122 - 62}{\text{Ln } 122/62} = 87.7^{\circ}\text{F.}$$

Area = Q/UxLMTD = 208,000/50 x 87.7

= 47.5 sq.ft.

The values of U (over-all heat transfer) and sizing of various control instruments and pumps are accepted by recommendation of various concerns manufacturing this equipment.

There are also numerous other details to the complete design such as the design of tower foundations, design of piping and structual supports, detailing, drafting, and cost analyses.

DISCUSSION

Although many plants, similar to the one described, have been designed, constructed and are operating according to guarenteed specifications, much remains to be desired in the good engineering of the design.

For a more rigorous approach the following data should be obtained.

1. Plate efficiency in contact tower and in the regenerator.

2. Hieght of a transfer unit, or of an equivilent theoretical plate, to be used in a packed-tower type of contactor or regenerator.

3. Better equilibrium data for the system, water-diethylene glycol and the system natural gas-water-diethylene glycol.

4. Complete cost analyses to determine economic optimum conditions of diethylene glycol rate, concentrations of diethylene glycol and number of trays for both contactor and regenerator.

The choice of equipment is rather flexible and depends upon economic considerations. In place of a regenerator with a bubble-cap column, it might be feasible to use an evaporator. It is also possible to use a small packed tower. The contactor, although usually designed with uptake pipes as indicated in

Diagram 1, may also use bubble-cap trays or slat-type packing.

It is the author's opinion that the contactor requires considerably more investigation. Since the pressure and gas capacity are both high, the contactor constitutes by far the largest expense for construction and errection. It is suggested that this expense can be markedly decreased by the use of a centrifugal contactor of the Podbilniak type, which gives excellent gas-liquid contact. No driving force need be applied to rotate the vanes; these vanes may be curved so that the velocity of the gas through the contactor spins them.

CONCLUSION

An attempt to follow the design philosophy for the dehydration of natural gas has been indicated. The design is neither academically elegant nor is it highly rigorous. That so many existing plants operate fairly successfully does not eliminate the need for more accurate experimental data and more scientific design; with better design and better data it should be possible to get more satisfactory and more economical operation.

SYMBOLS

A = Area, Square feet

G. = Moles of inert, dry natural gas per hour

H = Enthalpy Btu/lb. mole

H_s = Sensible heat Btu/lb.

L = Moles of dry diethylene glycol per hour

P = Pressure, pounds per square inch

Q = Heat transfered, Btu/hr.

^{o}R = Degrees Rankine = Degrees Farenheit 460

R = Gas constant, 10.71 $\frac{\text{lb./sq.in. x cu.ft.}}{\text{Lb.mole x }^{o}\text{R}}$

T = Temperature, Degrees Rankine

U = Overall coefficient of heat transfer, Btu/hr.sq.ft.^{o}F.

V = Volume, cu. ft.

X = Moles water per mole dry diethylene glycol

Y = Moles water per mole dry gas

Z = Compressibility factor

g = Gas gravity refered to air at same conditions

p = Vapor pressure

v = Velocity

Δ = Finite difference

ρ = Density lb./cu.ft.

c = Critical conditions

l = Liquid

r = Reduced property

sc = Pseudocritical conditions-refered to mixtures

v = Vapor

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